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# REGULATION OF INTRACELLULAR GLUCOCORTICOID CONCENTRATIONS

This invention relates to the interconversion of inactive 11-keto steroids with their active 11 $\beta$ -hydroxy equivalents, to methods by which the conversion of the inactive to the active form may be controlled, and to useful therapeutic effects which may be obtained as a result of such control. More specifically, but not exclusively, the invention is concerned with interconversion between cortisone and cortisol in humans.

10        Glucocorticoids such as cortisol have a number of diverse effects on different body tissues. For example, the use of cortisol as an anti-inflammatory agent was described in our International Patent Application WO 90/04399, which was concerned with the problem that therapeutically  
15 administered cortisol tends to be converted in the body to inactive cortisone by 11 $\beta$ -hydroxysteroid dehydrogenase enzymes. Our earlier invention provided for the potentiation of cortisol by the administration of an inhibitor of the 11 $\beta$ -dehydrogenase activity of these enzymes.

20        Another major physiological effect of cortisol is its antagonism to insulin, and it is known for example that high concentrations of cortisol in the liver substantially reduce insulin sensitivity in that organ, thus tending to increase gluconeogenesis and consequently raising blood sugar levels  
25 [1]. This effect is particularly disadvantageous in patients suffering from impaired glucose tolerance or diabetes mellitus, in whom the action of cortisol can serve to exacerbate insulin resistance. Indeed, in Cushing's syndrome, which is caused by excessive circulating  
30 concentrations of cortisol, the antagonism of insulin can provoke diabetes mellitus in susceptible individuals [2].

As mentioned above, it is known that cortisol can be converted in the body to cortisone by the 11 $\beta$ -dehydrogenase activity of 11 $\beta$ -hydroxysteroid dehydrogenase enzymes. It is  
35 also known that the reverse reaction, converting inactive

cortisone to active cortisol, is accomplished in certain organs by  $11\beta$ -reductase activity of these enzymes. This activity is also known as corticosteroid  $11\beta$ -reductase, cortisone  $11\beta$ -reductase, or corticosteroid  $11\beta$ -oxidoreductase.

It has only recently become apparent that there are at least two distinct isozymes of  $11\beta$ -hydroxysteroid dehydrogenase (collectively abbreviated as  $11\beta$ -HSD, which term is used, where appropriate, in this specification).

10 Aldosterone target organs and placenta express a high affinity NAD<sup>+</sup>-dependent enzyme ( $11\beta$ -HSD2) [3]. This has been characterised in placenta and kidney [4,5] and cDNA clones have been isolated [6,9].  $11\beta$ -HSD2 catalyses  $11\beta$ -dehydrogenase activity exclusively [4,7]. In contrast,

15 the previously purified, liver derived isozyme ( $11\beta$ -HSD1) is a lower affinity, NADP<sup>+</sup>/NADPH-dependent enzyme [10,11]. Expression of  $11\beta$ -HSD1 in a range of cell lines encodes either a bi-directional enzyme [11,12] or a predominant  $11\beta$ -reductase [13,15] which, far from inactivating

20 glucocorticoids, regenerates active  $11\beta$ -hydroxysteroid from otherwise inert 11-keto steroid.  $11\beta$ -reductase activity, best observed in intact cells, activates 11-keto steroid to alter target gene transcription and differentiated cell function [13,14].  $11\beta$ -HSD1 and  $11\beta$ -HSD2 are the products of

25 different genes and share only 20 % amino acid homology [6,7].

As far as the applicants are aware no previous attempts have been made to modify the action of  $11\beta$ -reductase. We have now found that it is possible to inhibit this activity

30 *in vivo*, and in doing so we have created the possibility of a novel medicament for use in treating many of the deleterious effects of glucocorticoid excess. In one aspect, therefore, the invention provides the use of an inhibitor of  $11\beta$ -reductase in the manufacture of a medicament for control

35 of 11-keto steroid conversion to  $11\beta$ -hydroxysteroid *in vivo*.

As mentioned above, one of the major physiological

effects of cortisol is insulin antagonism in the liver, and in a specific aspect the invention therefore provides the use of an inhibitor of  $11\beta$ -reductase in the manufacture of a medicament for inhibiting hepatic gluconeogenesis [1].

5 Cortisol promotes hepatic gluconeogenesis by several mechanisms, including antagonism of the effects of insulin on glucose transport, and interactions with insulin and glucose in the regulation of several enzymes which control glycolysis and gluconeogenesis. These include glucokinase,

10 6-phosphofructokinase, pyruvate kinase, phosphoenolpyruvate carboxykinase (PEPCK), and glucose-6-phosphatase. Inhibiting production of cortisol from cortisone in the liver therefore enhances hepatic glucose uptake and inhibits hepatic glucose production, by several mechanisms [16]. Moreover, the

15 influence of inhibiting  $11\beta$ -reductase activity in the liver of patients with insulin resistance or glucose intolerance may be greater than in healthy subjects because in insulin resistance or deficiency the influence of cortisol on PEPCK has been shown to be greater [17]; obese patients secrete

20 more cortisol [18]; insulin resistant patients are more sensitive to glucocorticoids [19]; and insulin down-regulates  $11\beta$ -HSD1 expression [15,20] so that  $11\beta$ -reductase activity may be enhanced in conditions of insulin resistance or deficiency.

25 Our studies have also shown that  $11\beta$ -HSD1 is expressed in rat adipose tissue and in adipocyte cell lines in culture, where it converts 11-dehydrocorticosterone to corticosterone (the rat equivalents of human cortisone and cortisol, respectively). This suggests that similar

30  $11\beta$ -reductase activity will be observed in human adipose tissue, with the result that inhibition of the enzyme will result in alleviation of the effects of insulin resistance in adipose tissue in humans. This would lead to greater tissue utilisation of glucose and fatty acids, thus reducing

35 circulating levels. The invention therefore provides, in a further aspect, the use of an inhibitor of  $11\beta$ -reductase in the manufacture of a medicament for increasing insulin sensitivity in adipose tissue.

The results of our studies have encouraged us to believe that inhibition of intracellular cortisol production will also lead to increased insulin sensitivity in other tissues which are acted upon by insulin, for instance skeletal muscle [21]. Inhibiting the  $11\beta$ -reductase therefore promises to reverse the effects of insulin resistance in muscle tissue, and to promote the up-take of essential molecules such as glucose and free fatty acids into muscle cells with consequent improved muscle metabolism and reduction of circulating levels of glucose and fatty acids. In a further aspect, the invention therefore provides the use of an inhibitor of  $11\beta$ -reductase in the manufacture of a medicament for increasing insulin sensitivity in skeletal muscle tissue.

It is also known that glucocorticoid excess potentiates the action of certain neurotoxins, which leads to neuronal dysfunction and loss. We have studied the interconversion between 11-dehydrocorticosterone and corticosterone in rat hippocampal cultures, and have found (surprisingly in view of the damaging effects of glucocorticoids) that  $11\beta$ -reductase activity dominates over  $11\beta$ -dehydrogenase activity in intact hippocampal cells [22]. The reason for this activity is unknown, but this result indicates that glucocorticoid excess may be controlled in hippocampal cells (and by extension in the nervous system in general) by use of an  $11\beta$ -reductase inhibitor, and the invention therefore provides in an alternative aspect the use of an inhibitor of  $11\beta$ -reductase in the manufacture of a medicament for the prevention or reduction of neuronal dysfunction and loss due to glucocorticoid potentiated neurotoxicity. It is also possible that glucocorticoids are involved in the cognitive impairment of ageing with or without neuronal loss and also in dendritic attenuation [23-25]. Furthermore, glucocorticoids have been implicated in the neuronal dysfunction of major depression. Thus an inhibitor of  $11\beta$ -reductase could also be of value in these conditions.

It will be appreciated from the foregoing that the

potential beneficial effects of inhibitors of  $11\beta$ -reductase are many and diverse, and it is envisaged that in many cases a combined activity will be demonstrated, tending to relieve the effects of endogenous glucocorticoids in diabetes mellitus, obesity (including centripetal obesity), neuronal loss and the cognitive impairment of old age. Thus, in a further aspect, the invention provides the use of an inhibitor of  $11\beta$ -reductase in the manufacture of a medicament for producing multiple therapeutic effects in a patient to whom the medicament is administered, said therapeutic effects including an inhibition of hepatic gluconeogenesis, an increase in insulin sensitivity in adipose tissue and muscle, and the prevention of or reduction in neuronal loss/cognitive impairment due to glucocorticoid-potentiated neurotoxicity or neural dysfunction or damage.

From an alternative point of view, the invention provides a method of treatment of a human or animal patient suffering from a condition selected from the group consisting of: hepatic insulin resistance, adipose tissue insulin resistance, muscle insulin resistance, neuronal loss or dysfunction due to glucocorticoid potentiated neurotoxicity, and any combination of the aforementioned conditions, the method comprising the step of administering to said patient a medicament comprising a pharmaceutically active amount of an inhibitor of  $11\beta$ -reductase.

As mentioned previously, the factors which control the relative activities of  $11\beta$ -dehydrogenase and  $11\beta$ -reductase in different conditions, especially by the  $11\beta$ -HSD1 isozyme, are poorly understood. It is likely that an  $11\beta$ -reductase inhibitor will be selective for the  $11\beta$ -HSD1 isozyme in vivo. We have found, for instance, that glycyrrhetinic acid (a known inhibitor of  $11\beta$ -dehydrogenase) has no effect on  $11\beta$ -reductase in vivo [26]. However, we have surprisingly found that carbenoxolone, which is known as an inhibitor of the  $11\beta$ -dehydrogenase enzyme, also inhibits  $11\beta$ -reductase in vivo [26,27]. In preferred embodiments, therefore, the



inhibitor is carbenoxolone (3 $\beta$ -(3-carboxypropionyloxy)-11-oxo-olean-2-en 30-oic acid), or a pharmaceutically acceptable salt thereof. The dose of carbenoxolone which we used in our studies was 100 mg every 5 8 hours given orally.

The invention is hereinafter described in more detail by way of example only, with reference to the following experimental procedures and results and the accompanying figures, in which:-

10 Figure 1 is a graph showing dextrose infusion rates (M values) after placebo or carbenoxolone administration, in an euglycaemic hyperinsulinaemic clamp study carried out on humans;

15 Figure 2 is a graph showing fasting plasma glucose concentrations in rats after placebo or carbenoxolone therapy at the daily doses indicated;

20 Figure 3 is a graph illustrating the effect of estradiol administration to gonadectomised or gonadectomised/adrenalectomised rats on hepatic 11 $\beta$ -HSD1 activity, and mRNA expression for 11 $\beta$ -HSD1 and PEPCK.

Figure 4 contains graphs of data obtained from mice which are either homozygous for the wild type 11 $\beta$ -HSD1 allele or which are homozygous for a knockout mutant allele for 11 $\beta$ -HSD1;

25 Figure 5 illustrates 11 $\beta$ -HSD1 enzyme activities and mRNA expression in undifferentiated and differentiated 3T3-F442A cells;

Figure 6 is a graph illustrating the effect of pretreatment with corticosterone and 11-30 dehydrocorticosterone with or without carbenoxolone, upon rat hippocampal cell survival on exposure to kainic acid.

## EXPERIMENTAL RESULTS IN SUPPORT OF THE INVENTION

### A. INSULIN SENSITIVITY

#### A.1 EFFECT OF CARBENOXOLONE ON INSULIN SENSITIVITY IN MAN

Consistent with the observations in animal tissues and  
5 cultured cells described above, we have established the  
relative activities of  $11\beta$ -dehydrogenase and  $11\beta$ -reductase  
in vivo in different organs in man by measuring the  
cortisol/cortisone ratio in plasma from selective venous  
catheterisations [28]. In most organs the venous effluent  
10 contains cortisol and cortisone in a ratio of  $\sim 10:1$ .  
However, in renal vein plasma the ratio is  $3:1$ , while in  
hepatic vein plasma the ratio is  $55:1$ , consistent with  
potent  $11\beta$ -dehydrogenase activity due to  $11\beta$ -HSD2 expression  
in the kidney and potent  $11\beta$ -reductase  $11\beta$ -HSD1 activity in  
15 the liver. Moreover, cortisone taken orally, and therefore  
delivered to the liver via the portal vein, is avidly  
converted on first pass to cortisol in the peripheral  
circulation [26,27]. Using this index of  $11\beta$ -reductase  
activity we have shown that, in addition to inhibiting renal  
20  $11\beta$ -dehydrogenase activity, carbenoxolone (but not  
glycyrrhetic acid) [26,27] inhibits hepatic  $11\beta$ -reductase  
activity in vivo in man.

In the liver, mineralocorticoid receptors are not  
expressed in significant numbers, but glucocorticoid  
25 receptors are abundant. Surprisingly, the affinity of  
glucocorticoid receptors for cortisol is 10-40 times lower  
than that of mineralocorticoid receptors [29]. It may be  
that, by contrast with the protection of high-affinity  
mineralocorticoid receptors from cortisol required of  
30  $11\beta$ -dehydrogenase activity in the distal nephron,  
 $11\beta$ -reductase activity in the liver is required to ensure  
that low-affinity glucocorticoid receptors get adequate  
exposure to cortisol. The free circulating concentrations of  
cortisol and cortisone are approximately equal, so that a  
35 large pool of cortisone is available for activation in the

liver. Such a mechanism would be analogous to the intra-cellular activation of other members of the thyroid-steroid hormone family which circulate in relatively inactive forms [30], such as testosterone which is converted 5 by 5 $\alpha$ -reductase to dihydrotestosterone, and thyroxine which is converted by 5'-monodeiodinase to tri-iodothyronine.

To test this hypothesis, we have used carbenoxolone to inhibit hepatic 11 $\beta$ -reductase, and observed changes in hepatic glucocorticoid receptor activation inferred 10 indirectly from changes in insulin sensitivity. Hepatic insulin sensitivity decreases and hepatic glucose production increases during both pharmacological [31,32] and physiological [33] increases in glucocorticoid levels. The results of these experiments were published [16] after the 15 filing of our British patent application number 9517622.8 on 29 August 1995.

#### Methods

Seven non-obese (Body Mass Index <25) healthy male Caucasian volunteers on no medication, aged 27-36 years, 20 were given carbenoxolone (100 mg every 8 hours orally) or matched placebo for seven days in a randomised double-blind cross-over design, with phases separated by at least 4 weeks. On the seventh day of each phase euglycaemic hyperinsulinaemic clamp studies with measurement of forearm 25 glucose uptake were performed, as described in detail in reference 16, the content of which is incorporated herein by reference.

#### Results

Carbenoxolone administration was associated with no 30 change in fasting glucose concentration but a fall in fasting insulin concentration. During the euglycaemic clamp, carbenoxolone enhanced the metabolic clearance rate of glucose (M values: 41.1  $\pm$  2.4  $\mu$ mol/kg/min for placebo versus 44.6 $\pm$ 2.3 for carbenoxolone;  $p<0.03$ ) (Figure 1). No 35 difference was detected in peripheral glucose uptake as measured by forearm glucose uptake, but this measurement was



less precise due to insulin-induced vasodilatation [34] and the mental stress induced by the restraint of the study conditions.

#### Discussion

5        These data show that carbenoxolone increases whole-body insulin sensitivity. This could have resulted from either increased suppression of hepatic glucose production as a reflection of increased hepatic insulin sensitivity, or increased peripheral utilisation of glucose as a reflection  
10 of increased peripheral insulin sensitivity. The absence of a change in forearm glucose uptake with carbenoxolone suggests that the former mechanism predominates. However, the imprecision of this measurement raises the possibility that there is a contribution from enhanced peripheral  
15 insulin sensitivity which we have not detected. A more detailed discussion of these data has now been published [16].

It is unlikely that carbenoxolone affects insulin sensitivity by a mechanism independent of its effect on  
20  $11\beta$ -reductase. Carbenoxolone inhibits other enzymes which metabolise cortisol, notably  $5\beta$ -reductase [35], but this effect would increase intra-hepatic cortisol concentrations and reduce insulin sensitivity. In the absence of corticosteroids, carbenoxolone at this dose has no  
25 documented effects in vivo and low affinity for corticosteroids receptors in vitro [36], so that a direct action of carbenoxolone to increase insulin sensitivity is unlikely. Indeed, previous experiments suggest that, at higher concentrations (mmol/l), carbenoxolone without  
30 corticosteroid antagonises the action of insulin in adipocytes [37]. Blood pressure and forearm blood flow were not elevated by carbenoxolone in this study, and even if they were this might be associated with reduced insulin sensitivity [34]. Finally, other neurohumoral changes  
35 consequent on the renal effects of carbenoxolone (suppressed plasma renin, aldosterone, and potassium concentrations) are not known to influence insulin sensitivity directly, and

in the context of oral sodium loading were associated with decreased insulin sensitivity [38].

From these observations we infer that basal  $11\beta$ -reductase activity plays a role in maintaining adequate exposure of glucocorticoid receptors to cortisol in human liver. The circulating pool of cortisone is therefore physiologically important as a source of active glucocorticoid in sites where  $11\beta$ -reductase is expressed.

#### A.2 EFFECT OF CARBENOXOLONE ON INSULIN SENSITIVITY IN THE RAT

Following our studies of the effects of carbenoxolone in healthy humans, we have performed unpublished studies of the effects of carbenoxolone in intact healthy rats. Consistent with the observations in human, we have shown that rat hepatocytes in primary culture express  $11\beta$ -HSD1 which has predominant  $11\beta$ -reductase activity [15]. We have also shown that the circulating concentration of 11-dehydrocorticosterone (measured by gas chromatography and mass spectrometry) is 40-50 nmol/l (Dr R Best, unpublished observation) so that there is a substantial pool of inactive 11-ketosteroid available for activation to corticosterone in sites where  $11\beta$ -reductase is active.

#### Methods

Intact male Wistar Hans rats of body weight 200-250 g were treated with daily subcutaneous injection of 1 ml of either 0.9% saline (vehicle) or carbenoxolone (made up to 1, 3, or 10 mg/ml in 0.9% saline) for 14 days. They were fasted from 4 pm and blood obtained by tail-nick at 9 am the next day. Plasma glucose was measured by a glucose oxidase method on a Beckman CX-3 autoanalyser.

#### Results

Carbenoxolone produced a dose-dependent fall in fasting glucose concentrations (Figure 2).

## Discussion

These experiments are preliminary, since it is now our intention to assess insulin sensitivity and glucose tolerance in rats treated with carbenoxolone. However, the fall in fasting plasma glucose is consistent with inhibition of hepatic gluconeogenesis with or without enhanced peripheral glucose uptake in rats treated with the 11 $\beta$ -reductase inhibitor carbenoxolone.

### A.3 EFFECT OF ESTRADIOL-MEDIATED INHIBITION OF HEPATIC 11 $\beta$ -HSD1 EXPRESSION ON INSULIN SENSITIVITY IN THE RAT

Having established the effects of a competitive pharmacological inhibitor of 11 $\beta$ -reductase activity on insulin sensitivity and glucose levels in man and rat, the object of this study was to examine the effects of down-regulation of transcription and translation of the 11 $\beta$ -HSD1 enzyme. The results of these studies have been presented at scientific meetings during 1996 but are not yet published.

11 $\beta$ -HSD1 expression is regulated by a variety of hormones *in vivo* [26]. In the rat liver, 11 $\beta$ -HSD1 shows pronounced sexual dimorphism, with lower activity in females. Indeed, chronic estradiol administration almost completely suppresses hepatic 11 $\beta$ -HSD1 expression in both male and female rats [39-41]. This regulation appears to be tissue- and isozyme-specific, as estrogen does not attenuate 11 $\beta$ -HSD1 expression in the hippocampus or 11 $\beta$ -HSD2 activity in the kidney [41]. The aim of this study was therefore to examine the contribution which reactivation of glucocorticoids by hepatic 11 $\beta$ -HSD1 makes to the expression of liver-specific glucocorticoid modulated genes in the rat by exploiting the selective suppression of hepatic 11 $\beta$ -HSD1 by estradiol *in vivo*.

## Methods

### *In-vivo studies*

Male Han Wistar rats (200-250 g) underwent gonadectomy

and either bilateral adrenalectomy or sham-operation under halothane anaesthesia. For estradiol administration, silicone elastomer capsules (1.95 mm internal diameter, 3.125 mm external diameter) (Dow Corning Corporation, 5 Midland, Michigan, USA) containing  $17\beta$ -estradiol (Sigma, Poole, UK) were implanted subcutaneously. For animals treated for 42 days with estradiol, the capsules were removed and replaced after 21 days. Control animals were implanted with blank capsules. Adrenalectomised rats were 10 maintained on 0.9% saline. Rats were killed 10, 21 or 42 days after surgery. Liver and hippocampus were removed and dissected on ice for assay of  $11\beta$ -HSD activity and an aliquot of liver was frozen on dry ice and stored at  $-80^{\circ}\text{C}$  until extraction of RNA.

15 *Quantitation of  $11\beta$ -HSD activity in in vivo experiments*

Tissues were homogenised in Krebs-Ringer bicarbonate buffer with 0.2% glucose, pH 7.4, and assayed as described previously [40]. Homogenates (6.25  $\mu\text{g}$  of liver protein, 250  $\mu\text{g}$  of hippocampal protein) were incubated with 200  $\mu\text{M}$  NADP 20 (Sigma, Poole, UK) and 12 nM [ $^3\text{H}$ ]-corticosterone (specific activity 84 Ci/mmol; Amersham International, Aylesbury, UK) in a total volume of 250  $\mu\text{l}$  with Krebs-Ringer buffer supplemented with 0.2% bovine serum albumin for 10 min at  $37^{\circ}\text{C}$ .  $11\beta$ -dehydrogenase activity was quantified in this 25 assay as a measure of active enzyme since  $11\beta$ -reductase is unstable in homogenates. Steroids were extracted with ethyl acetate and separated by HPLC with on-line  $\beta$  counter.  $11\beta$ -HSD activity was expressed as conversion of corticosterone to 11-dehydrocorticosterone, after correction 30 for apparent conversion in incubates without enzyme ( $<3\%$ ).

*Extraction and analysis of mRNA*

Total RNA was extracted from liver tissue by the guanidinium thiocyanate method, as described [40] and resuspended in diethylpyrocarbonate-treated water. RNA 35 concentration and purity was assayed spectrophotometrically. 20  $\mu\text{g}$  aliquots were separated on a 1.2% agarose gel containing 2% formaldehyde. RNA was blotted onto

nitrocellulose membranes (Hybond-N, Amersham International, UK), prehybridized in 6 ml phosphate buffer (0.2 M  $\text{NaH}_2\text{PO}_4$ , 0.6 M  $\text{NaH}_2\text{PO}_4$ , 5 mM EDTA), 3 ml 20% SDS and 100  $\mu\text{g}$  denatured herring testis DNA (Sigma, Poole, UK) for 2 h at 55°C and hybridized at 55°C overnight in the same solution containing rat 11 $\beta$ -HSD1 or PEPCK cDNA, labelled with  $^{32}\text{P}$ -dCTP using a random primed DNA labelling kit (Boehringer Mannheim UK Ltd., Lewes, UK). Three 20 min washes were carried out at room temperature in 1xSSC (0.3 M NaCl, 0.03 M sodium citrate), 0.1% SDS followed by a stringent wash at 55°C for 30 min in 0.3xSSC, 0.1% SDS. Filters were exposed to autoradiographic film for 1-4 days (adjusted to ensure the signal density was within the linear range). Filters were rehybridised with similarly labelled 7S cDNA or transferrin RNA cDNA probes to control for loading, as previously described [40] (transferrin mRNA expression is not altered by estradiol or glucocorticoid). Optical density was determined using a computer-driven image analysis system (Seescan plc, Cambs, UK). Values were expressed as a percentage of control levels.

#### Statistics

Data are the means $\pm$ SEM of 5-10 replicates (indicated in figure legends). Data were compared by ANOVA and Newman-Keuls post-hoc test or by Student's unpaired t-test, as appropriate. Statistical tests were carried out on absolute data, but the figures display data as percent of values for control animals to improve clarity.

#### Results

*Effect of chronic estradiol treatment on 11 $\beta$ -HSD1 activity and mRNA expression*

Estradiol administration for 10, 21 and 42 days to gonadectomised male rats resulted in marked decreases in hepatic 11 $\beta$ -HSD activity (Figure 3). However, 11 $\beta$ -HSD activity was not completely abolished since prolonged (60 min) incubation of liver homogenates from rats given estradiol for 42 days showed detectable (12.2 $\pm$ 14.7%)

conversion of corticosterone to 11-dehydrocorticosterone. 11 $\beta$ -HSD1 mRNA expression fell to undetectable levels after 21 and 42 days of estradiol treatment. 11 $\beta$ -HSD activity in the hippocampus was not altered by estradiol treatment at 21 or 42 days (data not shown).

*Effect of estradiol on hepatic glucocorticoid-inducible gene expression*

To examine the effect of attenuated hepatic 11 $\beta$ -HSD1 activity on local glucocorticoid action, the expression of 10 liver-specific glucocorticoid-inducible genes was measured after 42 days of estradiol. PEPCK mRNA expression was significantly reduced by estradiol treatment (Figure 3).

To examine whether these effects of estradiol on hepatic gene expression were mediated directly or via 15 alterations in glucocorticoid action in the liver, the effects of estradiol in adrenalectomised animals or sham-operated controls was examined. Animals were killed after 21 days. Plasma corticosterone values confirmed the adequacy of adrenalectomy (data not shown). Adrenalectomy 20 increased hepatic 11  $\beta$ -HSD1 gene expression and activity compared with sham-operated controls (Figure 3). Estradiol reduced liver 11 $\beta$ -HSD1 mRNA and activity in adrenalectomised rats, and although mRNA expression was higher than estradiol-treated adrenally-intact rats, it remained 25 significantly reduced compared with untreated controls.

Hepatic PEPCK gene expression was decreased after 21 days of estradiol treatment, albeit to a slightly lesser extent than after 42 days (Figure 3). Unsurprisingly, adrenalectomy also attenuated hepatic PEPCK gene expression, 30 but in adrenalectomised rats estradiol no longer reduced, but indeed increased PEPCK mRNA levels when compared with adrenalectomy alone.



## Discussion

Estradiol administration for both 21 and 42 days produced undetectable hepatic  $11\beta$ -HSD1 mRNA expression and markedly reduced  $11\beta$ -HSD activity (although this remained clearly measurable), confirming previous studies [41]. The discrepancy between mRNA expression and activity might be due to much slower turnover of  $11\beta$ -HSD1 protein or, more likely, to the transcription and translation of residual low levels of  $11\beta$ -HSD1 mRNA, undetectable by northern analysis. This effect of sex steroids is relatively specific to the liver, since hippocampal  $11\beta$ -HSD1 was unaffected, and previous studies have shown that  $11\beta$ -HSD2 is not attenuated by estrogens [22]. Thus the advantage of exploiting estrogen down-regulation of hepatic  $11\beta$ -HSD1, as opposed to conventional carbenoxolone or other inhibitors of the enzyme, is that  $11\beta$ -HSD2 is unaffected.

Following 42 days of estradiol treatment, hepatic expression of mRNA encoding PEPCK was clearly reduced. In principle, this effect of chronic estrogen treatment may be explained in several ways: (i) estrogen may act directly to repress hepatic gene expression; (ii) estradiol may alter corticosteroid metabolism in the liver. Reduced hepatic  $11\beta$ -HSD1-mediated reactivation of otherwise inert 11-dehydrocorticosterone is anticipated to reduce expression of these glucocorticoid-sensitive transcripts; (iii) there may be other indirect effects of chronic estradiol administration.

For PEPCK direct inhibition by estradiol appears unlikely, since this transcript was induced by estrogen in adrenalectomised rats. The loss of the attenuating effect of estradiol on PEPCK expression in adrenalectomised rats suggests a requirement for glucocorticoids in the process, rather than any other indirect effect. Glucocorticoids increase expression of PEPCK in the liver [17] and so this pattern of changes is compatible with the glucocorticoid control of expression of this gene. The effect of estradiol in intact rats was as potent as adrenalectomy alone in

attenuating PEPCK mRNA expression. These data are therefore consistent with the effects of estradiol being indirectly mediated via the marked loss of  $11\beta$ -HSD1  $11\beta$ -reductase activity, which thus attenuates intrahepatic glucocorticoid 5 regeneration. Thus the  $11\beta$ -reductase activity of  $11\beta$ -HSD1 is likely to be of key importance in producing sufficiently high intrahepatic corticosterone levels to elevate PEPCK above the minimum levels maintained by basal (non-glucocorticoid) factors.

#### 10 A.4 EFFECT OF TRANSGENIC KNOCKOUT OF $11\beta$ -HSD1 EXPRESSION

Although the effects of carbenoxolone and estrogen-induced downregulation of  $11\beta$ -HSD1 expression provide strong support for our hypothesis that  $11\beta$ -reductase inhibition will enhance insulin sensitivity and reduce 15 hepatic glucose production, both of these agents are potentially confounded by other actions, including direct effects on  $11\beta$ -HSD2 (carbenoxolone) and other effects on the liver (estrogen). The most clear-cut evidence of the importance of a specific protein can now be tested most 20 effectively using transgenic technology. We have now produced a transgenic mouse which is homozygous for a mutant allele carrying a targetted disruption of the  $11\beta$ -HSD1 gene. Some of these results have been presented at scientific meetings during 1996 but have not yet been published.

#### 25 Methods

A mouse genomic library constructed from isogenic OLA129 DNA in the lambda vector GEM12 was screened with a rat  $11\beta$ -HSD1 cDNA probe. A lambda phage containing a 14 kb insert encompassing exons 2 to 5 of the mouse  $11\beta$ -HSD1 gene 30 was cloned and subjected to extensive restriction mapping and sequence analysis. Using this information, a replacement vector 16 Kpn $\beta$ A was constructed using the pBS-KpnA cassette. The vector consisted of the neomycin resistance gene under the control of the human  $\beta$ -actin promoter and followed by 35 the SV40 polyadenylation signal. The 6.5 kb long 3' homology arm was subcloned from intron D. The 1.2 kb short homology

arm was synthesised by PCR using high fidelity Ultma Taq polymerase, 129 mouse genomic DNA and primers bearing nested Sac I and Spe I restriction sites and located in exon 1 and intron 3. An external probe was synthesised by PCR. Using this probe, a specific recombination event generates a 1.5 kb *Bam*HI fragment instead of a 3 kb fragment expected for the wild type gene.

Following transfection of the 16 *Kpn*β A replacement construct into 'CGR 8' embryonic stem cells, of 368 10 neomycin-resistant colonies screened, only one showed homologous recombination at the 5' end. The specificity of the recombination event was tested by Southern blot hybridisation after *Bam*HI restriction. Specificity of restriction at the 3' end was also confirmed by 15 hybridisation with an internal probe after three different restrictions.

Positive embryonic stem cells were injected into C57B1/6 blastocysts to generate chimeric offspring who were crossbred to establish a colony of homozygotes for the 20 knockout allele.

## Results

Homozygotes for the mutant allele are morphologically intact and fully fertile. No survival bias is conferred by the mutant allele. However, neither 11β-HSD1 mRNA nor enzyme 25 activity (techniques as above) were detected in mutant homozygotes, and reduced mRNA and activity were detected in heterozygotes. Plasma corticosterone levels are not altered in mutants, but the ratio of corticosterone to 11-dehydrocorticosterone in urine is markedly reduced. 30 Homozygous mutant mice are also unable to convert 11-dehydrocorticosterone to corticosterone *in vivo* and are thus resistant to the thymic involution seen with 11-dehydrocorticosterone in wild-type control mice.

Animals were fasted for 48 hours before sacrifice and 35 collection of trunk blood. Plasma glucose was measured by a

glucose oxidase method (see above). Fasting plasma glucose concentrations were lower in mutant animals (Figure 4).

Measurement of enzymes responsible for hepatic glycolysis/gluconeogenesis revealed no differences between wild type and mutant animals in the fed state. However, on fasting the mutant animals failed to show the normal induction of glucose-6-phosphatase and PEPCK (Figure 4). Glucokinase was not altered.

#### Discussion

These data demonstrate the importance of  $11\beta$ -HSD1 in hepatic glucose metabolism and insulin sensitivity. Glucose-6-phosphatase and PEPCK are two gluconeogenic enzymes which are down-regulated by insulin and up-regulated by glucocorticoid exposure [1]. In the presence of insulin (in fed animals) there is no change in expression of these enzymes, confirming that insulin regulation is dominant. However, in starved animals with low insulin levels there is a failure of induction of these enzymes consistent with a failure of corticosterone-dependent induction. In animals in which the mutant vector has recombined specifically to knockout only  $11\beta$ -HSD1, and in which plasma corticosterone is maintained by normal hypothalamic-pituitary-adrenal feedback these changes can be attributed to impaired intra-hepatic conversion of 11-dehydrocorticosterone to corticosterone.

#### A.5 ROLE OF $11\beta$ -HSD1 IN ADIPOCYTE MATURATION

Glucocorticoids are involved in triggering adipocyte differentiation from uncommitted adipoblasts into committed preadipocytes. Glucocorticoid excess in humans causes profound changes in both adipose tissue distribution and metabolism [18]. In Cushing's syndrome, omental fat shows adipose cell hyperplasia, associated with enhanced lipoprotein lipase and glycerol-phosphate dehydrogenase activity. In homogenised adipose tissue cortisol and corticosterone are oxidised to cortisone and

11-dehydrocorticosterone, indicating the presence of  $11\beta$ -HSD [42] which might modify glucocorticoid action in a site- and developmentally-specific manner. We have (i) examined the expression of  $11\beta$ -HSD enzyme activity and  $11\beta$ -HSD mRNA in 5 isolated primary rat adipocytes; and (ii) determined whether  $11\beta$ -HSD is expressed in a fibroblast derived clonal cell line, 3T3-F442A which can be induced into mature adipocytes in presence of fetal calf serum and insulin. The results of this work have not been published.

## 10 Methods

### *Animals*

Epididymal adipose tissue was excised from adult male Wistar rats. Adipose tissue was washed several times in Phosphate Buffered Saline, trimmed of large blood vessels 15 and minced. Tissue was incubated in Krebs-Ringer buffer (KRB) containing collagenase II (2 mg/ml) (Sigma, UK) at 37°C for 40 min, and the digested material passed through a 250  $\mu$ m nylon filter and briefly centrifuged. The separated adipocyte (floating) and stromal vascular (pellet) fractions 20 were collected for (i) RNA extraction and northern blot as described above and (ii)  $11\beta$ -dehydrogenase bioactivity assay as described above, using final concentrations of 500  $\mu$ g protein/ml, 200  $\mu$ M cofactor (NADP or NAD), and 12 nM 1,2,6,7- $^3$ H-corticosterone in a total volume of 250  $\mu$ l 25 Krebs-Ringer buffer for 15 min at 37°C.

### *Cell culture*

Clonal preadipocyte cell lines 3T3-F442A, (kindly provided by Dr. Pairault Henri Modor Hospital, Creteil, France) were plated at a density of  $10^4$  cells/100 mm diameter 30 dishes in 'basal medium' (Dulbecco's modified Eagle's medium (DMEM), supplemented with 10% newborn calf serum, penicillin 200 U/ml and streptomycin 50  $\mu$ g/ml). To differentiate confluent 3T3-F442A cells, basal medium was replaced with 'differentiation medium' (DMEM, 10% fetal calf serum and 35 insulin, 5  $\mu$ g/ml) and maintained in this for 11 days with the medium changed every 48 h.

11 $\beta$ -Dehydrogenase and 11 $\beta$ -reductase activities were measured in intact cells by addition of 25 nM corticosterone with labelled <sup>3</sup>H-corticosterone or 25 nM 11-dehydrocorticosterone with labelled <sup>3</sup>H-11-dehydrocorticosterone. Interconversion of corticosterone and 11-dehydrocorticosterone was assessed as above at 3, 8 and 24 h after the addition of steroids.

### Results

Extracts from homogenized rat adipocytes showed 11 $\beta$ -HSD activity, as demonstrated by conversion of corticosterone to 11-dehydrocorticosterone. 11 $\beta$ -HSD1 was transcribed in whole white adipose tissue and isolated adipocytes as a single, approximately 1.6kb species of mRNA, of similar size to the hepatic species, though expression was lower than in liver. 11 $\beta$ -HSD1 transcripts were also expressed in the stromal vascular fraction (data not shown).

3T3-F442A cells were induced to differentiate and, after 10 days, >90% cells were differentiated as determined by visible lipid accumulation. Associated with this differentiation there was a marked increase in 11 $\beta$ -HSD1 mRNA expression and 11 $\beta$ -reductase activity which occurred late (8 days after addition of differentiation medium) and in association with induction of GPDH expression. (Figure 5).

### Discussion

In this study, we have demonstrated 11 $\beta$ -HSD1 gene expression in rat adipose tissue and isolated rat adipocytes, as well as the stromal vascular preadipocyte fraction, in agreement with data demonstrating 11 $\beta$ -HSD activity in the adipose component of the mammary gland [42]. By contrast with data obtained in homogenised tissue and in keeping with findings in other whole cell preparations [15,22], we have found in whole cells that 11 $\beta$ -HSD1 operates as an 11 $\beta$ -reductase rather than 11 $\beta$ -dehydrogenase enzyme. In addition, in the 3T3-F442A cell line, we have demonstrated that 11 $\beta$ -HSD1 expression is regulated in a differentiation-dependent manner. 11 $\beta$ -HSD1 thus has the



characteristics of a 'late' differentiation gene. Moreover, the regulated expression of  $11\beta$ -HSD1 paralleled that of GPDH, a glucocorticoid-sensitive late marker of adipocyte differentiation.

5        These results support the hypothesis that  $11\beta$ -reductase plays a physiological role in converting 11-keto steroids to  $11\beta$ -hydroxy steroids and thus amplifying glucocorticoid activity. In the adipocyte this may explain the induction of GPDH. Although inhibition of  $11\beta$ -reductase would not be  
10 expected to influence the early differentiation of adipocytes, it may influence the biochemical phenotype of differentiated cells, specifically in relation to lipid metabolism.

#### B NEURONAL EFFECTS OF $11\beta$ -REDUCTASE INHIBITORS

15        Several studies have demonstrated  $11\beta$ -HSD activity, immunoreactivity and mRNA expression in hippocampal neurons [43]45. Administration of  $11\beta$ -HSD inhibitors alters functional activity in the hippocampus *in vivo* [46], although the mechanisms underpinning this effect are  
20 obscure.

Previous studies have shown that in homogenates of hippocampus, both dehydrogenation and reduction occur [44], but the reaction direction in intact cells was previously unknown. We have now examined  $11\beta$ -HSD activity and its  
25 function in primary cultures of fetal hippocampus cells. The results of these experiments were published [22] after the filing of our patent application number 9517622.8 on 29 August 1995. Further details of the experiments will be found in reference 22, the contents of which are  
30 incorporated herein by way of reference.

#### Methods and Results

Hippocampi were dissected from Wistar rat embryos on day 18.5 of pregnancy and cultured in DMEM with supplements, as described [22]. These cells expressed  $11\beta$ -HSD1 mRNA, and

homogenised cells performed either  $11\beta$ -dehydrogenase or  $11\beta$ -reductase activity. However, in whole cells in culture, only  $11\beta$ -reductase activity was demonstrated. This  $11\beta$ -reductase activity could be almost abolished by the addition of carbenoxolone ( $10^{-6}$ M) [22].

To assess the influence of  $11\beta$ -reductase activity on neurotoxicity, cells were exposed to kainic acid and cell survival determined. Both corticosterone and 11-dehydrocorticosterone potentiated kainic acid neurotoxicity. However, carbenoxolone did not alter the effect of corticosterone, but protected the cells from the potentiating effect of 11-dehydrocorticosterone (Figure 6).

#### Discussion

These data demonstrate that  $11\beta$ -HSD1 is an  $11\beta$ -reductase enzyme in rat hippocampus and that the conversion of 11-ketosteroids to 11-hydroxysteroids potentiates the neurotoxic action of glucocorticoids. Importantly, they show that inhibition of  $11\beta$ -reductase activity can protect the cells from the damage that occurs due to reactivation of 11-dehydrocorticosterone. This supports the hypothesis that inhibition of  $11\beta$ -reductase in human brain would prevent reactivation of cortisone into cortisol and protect against deleterious glucocorticoid-mediated effects on neuronal survival and other aspects of neuronal function, including cognitive impairment, depression, and increased appetite.

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